Met Office
Hadley Centre

Climate risk

An update on the science

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- Recent observations provide further insight into how the climate system continues to change. The changes we measure are consistent with a view of a warming world. It is now evident that human influence is not only driving long-term trends in metrics such as global average temperature but is also already impacting on the risk of weather extremes. These extremes have implications for people, infrastructure and natural systems.

- Climate models are able to simulate many features of observed climate variability and change, giving confidence in their ability to simulate future climate. Recent model simulations highlight the urgency of making sizeable emissions reductions if the world is to have an acceptable chance of limiting warming to no more than 2 ºC above pre-industrial levels. Using the IPCC's highest representative concentration pathway, which portrays a world without emissions reduction policy, the 2 ºC limit could be exceeded within a few decades and likely before the middle of the century.

- An increasing number of climate impact simulations are highlighting the potential consequences of unchecked increases in emissions. A robust picture is emerging of the types of potential threat, including on the local scales at which people live and work. Furthermore, new developments in climate modelling, which enable us for the first time to look at very fine spatial details, are suggesting additional risks associated with increases in intense rainfall.

- Climate science has helped define the challenges and opportunities from future changes in climate. It is now increasingly focused on providing information to help to manage the future risks of climate change. This includes a better understanding of the rate and scale of global change for mitigation choices and regional scenarios of future extreme weather for adaptation planning. This work is helping to inform the dialogue on the long-term climate goal.

Introduction

The world is warming and we can see evidence of this throughout the climate system, including increasing temperatures, rising sea levels, shrinking glaciers and reducing extent and thickness of Arctic sea ice. These changes present a consistent picture of how we might expect climate change to manifest itself as the planet continues to warm. It is now possible to link observed changes in many aspects of the climate to human influence. However, it remains difficult to detect changes in regional rainfall and drought above natural variability.

Here we present an update on some of the key science undertaken at the Met Office Hadley Centre in collaboration with other institutes, since the Intergovernmental Panel on Climate Change Fifth Assessment (IPCC AR5) Working Group I report was released in September 2013. The evidence we present supports the key conclusions of the IPCC assessment. We provide the latest evidence of climate change and show how the link to human influence is getting ever more robust. Recent extreme events — for example, drought in California and record heat in Australia — demonstrate the exposure and vulnerability of human systems to climate variability and change. Our latest understanding of whether human activity has a role in these events is presented in this report.

Climate change poses risks for human and natural systems. The climate science community is increasingly focussing on providing the information that society needs to manage these risks and also to exploit emerging opportunities. Future risk can be reduced and managed through mitigation and adaptation measures. At the Met Office Hadley Centre — a world leader in climate research, modelling and projections — we play a key role in providing scientific evidence to help inform UK Government policy.

Here we provide new information on changing rainfall extremes for adaptation planning. We highlight the latest research on climate impacts and show how mitigation choices affect the rate and scale of climate change. These results emphasise the urgent need to reduce greenhouse gas emissions if damage to the climate system is to be minimised.

The Met Office Hadley Centre Climate Programme is funded by the UK Government through a three-year focused research programme currently spanning 2012–2015. We work collaboratively with other leading academic and research organisations to advance the science and skill of climate prediction, in support of the National Climate Capability. Additionally, we play a key role in many EU-funded projects, including EUCLEIA (European Climate and Weather Events: Interpretation and Attribution), EUPORIAS (European Provision of Regional Impacts Assessments on Seasonal and Decadal Timescales) and HELIX (High-End Climate Impacts and Extremes).

Observations

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Even stronger evidence that our climate is changing.

One of the key results of the IPCC AR5 is that most of the warming of the Earth's surface since the mid-20th century is very likely due to increases in carbon dioxide (CO_2) and other greenhouse gases. Ice core records show that, until the early 20th century, CO_2 concentration in the atmosphere did not exceed 300 parts per million (ppm) during the previous 800,000 years. In May 2013, at Mauna Loa Observatory in Hawaii, CO_2 levels briefly exceeded 400 ppm. During 2014, for the first time, monthly averages for April, May and June were all above 400 ppm.

The Met Office, together with many other centres around the world, monitors a wide range of climate variables in order to build a comprehensive understanding of the climate. These include sea-level, ocean heat content, land- and sea-ice, atmospheric humidity and temperature.

Global sea level is an important indicator of climate change and measurements show it has been rising over the past century. The rate of increase has been greater in recent decades and the latest measurements show a rise of around 3 mm per year. This increase is mainly due to thermal expansion of the oceans and melting of ice on land. It is highly likely that 2013 will have been the 24th successive year showing a loss of glacial ice.

Globally-averaged near-surface temperature is often used as a primary metric for climate change. In 2013, this temperature was between 0.49 and 0.51 °C above the 1961–1990 average depending on which of three independent datasets was used (Figure 1). Allowing for uncertainty arising from, for example, gaps in data coverage, 2013 most likely ranks in the top 10 warmest years in the 164-year record. The first nine months of 2014 were warmer than the long-term average, with May, August and September being exceptionally warm in all datasets. At the time of writing, it is looking like 2014 will also rank in the top 10 warmest years. Despite this, there has been a recent slowdown in the *rate* of global temperature rise which is discussed on page 7.

In 2013, Australia had its warmest year since national records began in 1910. Far western Asia also saw very high annual temperatures. Unusually high temperatures were widespread, including across much of Eurasia, Africa, the North Atlantic, the Indian Ocean and western Pacific. However, a swathe of central North America and the eastern Pacific had cooler than average temperatures (Figure 2).

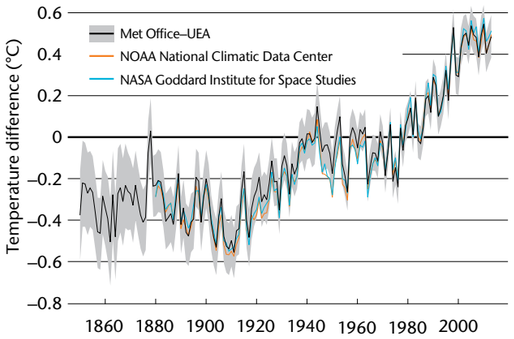

Figure 1: Observed annual global average near-surface temperatures for 1850–2013 relative to 1961–90 for three datasets. Grey shading shows 95% confidence range for HadCRUT4. Source: HadCRUT4 (Met Office–University of East Anglia); MLOST National Climatic Data Center (NOAA); Goddard Institute for Space Studies (NASA).

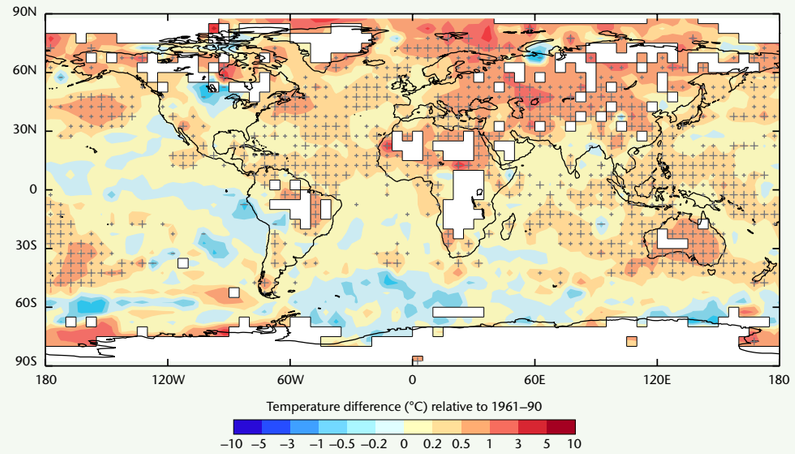

Figure 2: Observed annual near-surface temperatures for 2013 relative to the 1961–90 average. Source: HadCRUT4 (Met Office–University of East Anglia). The crosses indicate where temperatures exceed the 90th (small crosses) and 98th (large crosses) percentiles of the 1961–1990 distribution; and dashes where they are below the 10th (small dashes) and 2nd (large dashes) percentiles. White boxes indicate missing or insufficient data.

Changes in the frequency and intensity of heatwaves and cold snaps can arise from long-term changes in the climate. This has implications for human and animal health, crop production and for infrastructure. Globally, 2013 had the warmest set of daily maximum temperatures on record. This continues the trend towards warmer extreme temperatures. Across Australia, a total of 44 stations, each with more than 30 years of data, experienced record daily maximum temperature. Globally, 2013 was also in the top 10 years for the number of warm days and in the bottom 10 years for the number of cool nights since records began in 1950 (Figure 3).

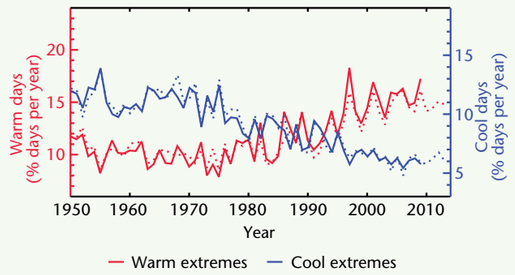

Figure 3: Observed global average frequency of warm and cool extremes from 1950 to 2013. Two datasets are shown: GHCNDEX (dotted) and HadEX2 (solid) (both available from www.climdex.org). Warm extremes are those days which have a maximum temperature exceeding the 90th percentile. Cool extremes are those days where the minimum temperature drops below the 10th percentile. Percentiles are calculated over the 1961–90 base period.

Approaching El Niño

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Natural climate variability can modulate the rate of global temperature rise.

Regular near-term climate predictions out to seasons or years ahead are made by the Met Office Hadley Centre and other climate-prediction centres around the world. These climate predictions focus on the risk of impending extreme events or other changes in the climate system. Large areas of the tropical oceans are highly predictable on timescales out to months ahead and the El Niño Southern Oscillation (ENSO) in particular shows high levels of such predictability. Recent work at the Met Office Hadley Centre shows signs of predictability outside the tropics, with exciting prospects for improved seasonal predictions of European and North American winter conditions.

The past year has seen changes taking place at and below the surface of the equatorial Pacific Ocean that suggest the possible onset of an El Niño event. However, despite early indications, the atmosphere has so far largely failed to reinforce these changes. The Met Office assessment made in early 2014 was that any El Niño would likely be weak to moderate. This forecast has remained consistent throughout and contrasts with some other leading prediction centres that initially suggested a strong event. As of late 2014, ENSO indicators are neutral, although equatorial Pacific Ocean temperatures are slightly above normal. Current outlooks for boreal winter 2014/15 suggest neutral or weak conditions are most likely.

El Niño has significant impacts across the globe, including stronger East Pacific tropical cyclone activity, less Atlantic hurricane activity and drier conditions over Indonesia, Australia and parts of South America (Figure 4).

El Niño is the most important expression of year-to-year variability.

El Niño and La Niña events, which recur irregularly every few years, are the two sides of a naturally occurring cycle involving the ocean and atmosphere. El Niño events are characterised by warmer than normal sea-surface temperatures in the tropical Pacific. These changes impact the prevailing winds in a way that is self-sustaining for several seasons. El Niño events have the potential to cause major climatic impacts around the world, demonstrating our exposure and vulnerability to climate variability and change.

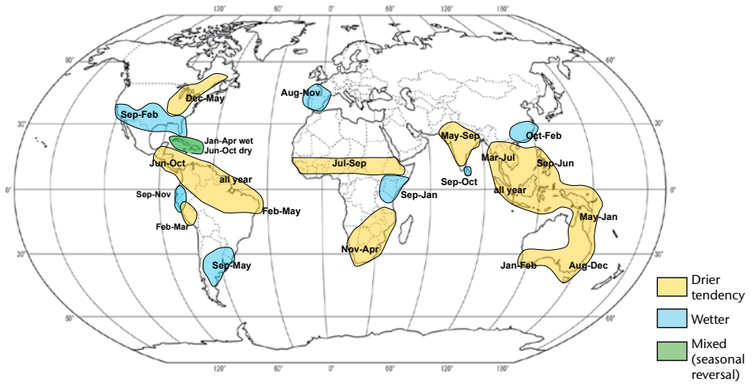

Figure 4: Schematic summary of the historical impacts of El Niño on precipitation across the globe.

Global warming slowdown

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The rate of surface warming has slowed over the last 15 years, but this slowdown is not expected to continue indefinitely.

Despite increasing concentrations of greenhouse gases in the atmosphere, the rate of warming of the global mean surface temperature has slowed over the last 15 years or so. A new analysis of the HadCRUT4 surface temperature dataset[1], using different methods to account for sparse Arctic measurements, shows a slightly higher warming trend over the period 1998–2012 of 0.11 °C per decade compared to the previous estimate of 0.04 °C per decade. However, a slowdown in warming is still evident, with the rate of warming over the longer period 1979–2012 being 0.16–0.18 °C per decade, depending on the analysis method used. A similar slowdown has not been seen in other climate change indicators such as the rate of sea level rise or in the increase in ocean heat content (Figure 5).

The surface warming slowdown has been linked in part to decadal changes in the circulation of the Pacific Ocean, with a potential role of circulation changes in the North Atlantic. A greater fraction of stored energy appears to be temporarily residing in the deep ocean, rather than warming the surface. These ocean circulation changes may be due to naturally occurring decadal variability.

A component of the slowdown may also be due to a reduction in the amount of energy entering the Earth's system. Updated estimates highlight the potential role of reduced solar activity, minor volcanoes and possible underestimates of aerosol effects. Aerosols, both from volcanoes and human emissions, cool the Earth's surface by reflecting solar energy back into space.

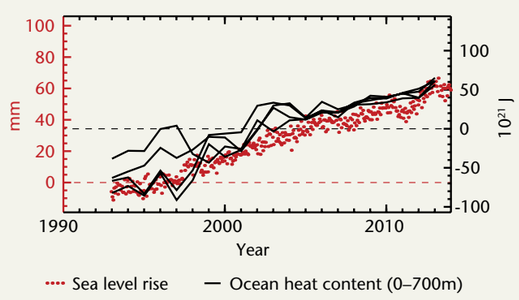

Figure 5. Observed global average sea level rise and change in ocean heat content from 1993 to 2013. Sea-level data from a combination of TOPEX (1993–2001), Jason-1 (2002–08) and Jason-2 (2008–13) (available from http://sealevel.colorado.edu/). Ocean heat content is for the top 700 m relative to the 1993–2012 average: data from CSIRO/ACE CRC; PMEL/JPL/JIMAR; NODC; and EN4.0.2 (Met Office).

They also have an indirect — and much more uncertain — effect on the climate by altering the brightness and lifetime of clouds.

These factors suggest the slowdown in surface warming is likely to be temporary. Similar periods of slowdown lasting a decade or so have been seen in the past in observations and climate model simulations.

[1] K. Cowtan and R. G. Way, 2013. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. ***Quarterly Journal of the Royal Meteorological Society***, doi: 10.1002/qj.2297.

Evidence of human influence on extremes

Even stronger evidence that human activity is affecting the climate, not just the mean climate but also the extremes.

As the world as a whole warms, climate change is most apparent in extremes. The evidence for human influence on extremes has strengthened, with the IPCC concluding that it has now very likely contributed to observed global-scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century.

The vulnerability of society was demonstrated during the European summer heatwave of 2003, which could have led to as many as 70,000 extra deaths. The first attribution study on the 2003 heatwave showed that human influence at least doubled the odds of such an event. Since then, the probability of very warm European summer temperatures has increased considerably and will keep increasing in the future as greenhouse gas emissions increase (Figure 6a). In particular, heatwaves as severe as that in 2003 are expected to occur about once a century for the current climate, whereas in the early 2000s they were expected to occur, on average, once every several thousand years. By the 2040s, a summer as hot as 2003 could be very common.

Other regions and seasons are also seeing considerable increases in the probability of very warm temperatures. In 2013, Australia had its hottest year on record, with September 2013 having the largest temperature anomaly for any calendar month on record. Human influence considerably increased the likelihood of such an event. The plots in Figure 6 are illustrative of the changing probabilities of anomalously warm seasons arising from human influence. Computer model simulations which include both historical human and natural factors better fit the observed climate than if only historical natural factors are included.

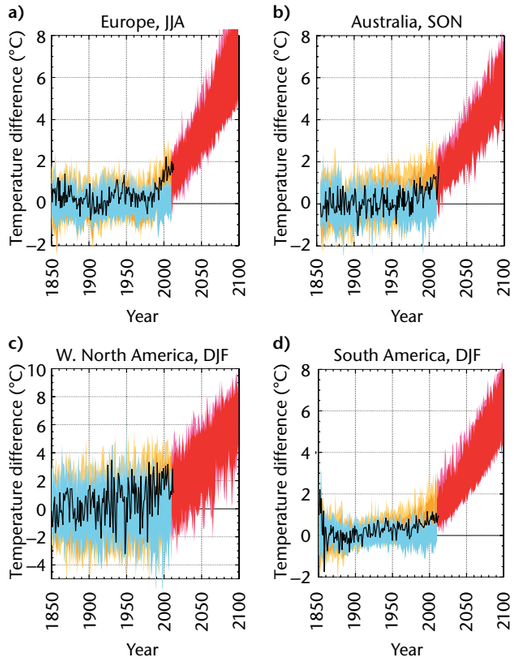

Figure 6: Temperature anomalies with respect to 1880–1919 for (a) Europe, summer; (b) Australia, spring; (c) western North America, winter; (d) South America, summer; from observations (black) and for simulations using historical man-made and natural forcings (orange), historical natural forcings only (blue) and high emissions scenario RCP8.5 (red). Note different temperature scale in 6 (c).

In general, temperature variability tends to be larger in winter than in summer, and so detecting a climate warming signal is more difficult in the cold part of the year. This is illustrated in Figure 6c, with large temperature variability for western North America in winter.

Global precipitation patterns are changing, but precipitation events are strongly influenced by natural variability — making attribution to human influence difficult at present. However, taking the water cycle as a whole, the IPCC AR5 concluded that human activity has likely influenced the global water cycle since 1960. This is important because any changes will have serious implications for the management of water resources. Extremes linked to the water cycle — such as droughts, heavy rainfall and floods — are already causing substantial damage. In 2013–14, California had its third driest rainy season (November–February) on record. Initial studies of this event indicate that human influence was not found or was uncertain.

Evidence from multiple sources indicates that human influence has on average changed the frequency of high-impact temperature and precipitation extremes over land, where there are sufficient observational data to make this assessment. Providing an authoritative assessment of the role of climate change in individual recent extreme events, however, remains a major challenge. The Met Office Hadley Centre has played a key role in examining the causes of extreme events world-wide in the last few years (Figure 7 overleaf). The number of studies, which is not indicative of the number of events, has increased in recent years. Of the events studied that took place in 2013, 10 out of 16 were found to have had a human influence on their likelihood of occurrence. One study, led by the Met Office Hadley Centre, looked at the particularly cold UK spring of 2013, the coldest for more than 50 years. It found that the event was associated with an unusual circulation pattern, but that human influence had made cold temperatures in such a situation much more unlikely, by more than 30 times. Such an event has now become more unusual due to human-induced climate change.

The Met Office is leading on the EU-funded EUCLEIA project, launched in early 2014. This will assess the change in risk of extremes arising from climate change and provide products to targeted stakeholders to develop climate adaptation strategies.

How quickly will the world warm?

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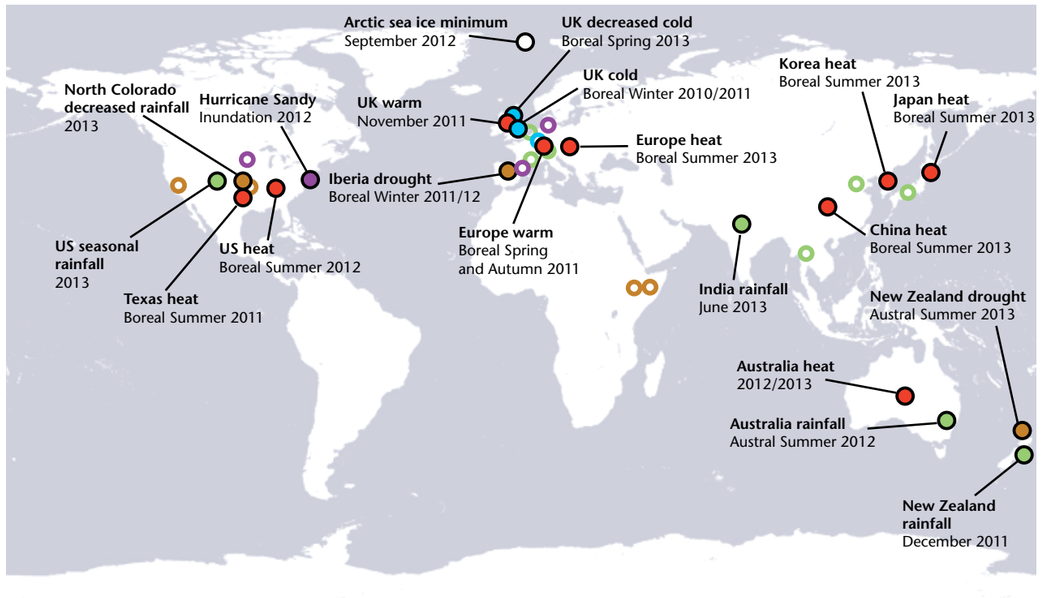

Figure 7: Extreme events in 2011–13 studied in Explaining Extreme Events from a Climate Perspective: Special Supplement to the *Bulletin of the American Meteorological Society*.

Potentially dangerous climate change may be closer than we thought.

We need to better understand the rate at which climate change will occur. Rapid changes place much greater pressure on implementing adaptation measures and highlight the urgency of responding to climate change. A new comprehensive assessment of the time to reach specific warming levels has examined the models and scenarios from the first working group of the recent IPCC AR5 as well as results from a large ensemble of Met Office Hadley Centre models, in which key model parameters are systematically varied.

The climate model simulated time at which a specific global warming level may be reached depends on past and future emissions of greenhouse gases. Emissions scenarios with little or no climate policy consistently have the earliest time of reaching various warming levels (Figure 8). The simulated time to reach a specific warming level also varies across climate models. This depends on how a range of climate processes, such as the behaviour of clouds and the rate of ocean heat uptake, are simulated within the model.

For the high emissions RCP8.5 scenario, which is often regarded as a "business as usual" world, global warming of 2 °C will most likely be reached between 2020 and 2048 (10–90th percentile range of the CMIP5 and Met Office Hadley Centre perturbed physics models). For 4 °C global warming, the likely range is 2054–2087.

From the perspective of climate impacts, the regional and local changes are important. Most land areas pass a given warming level much earlier than the global average and there is also clear evidence of amplified warming over northern high latitudes. The physical causes of the amplified warming in model simulations of the future are well understood in many cases and it is a robust feature of the future projections.

This work is currently being extended in the EU HELIX project to include all of the emissions scenarios covered by the third working group of the IPCC AR5.

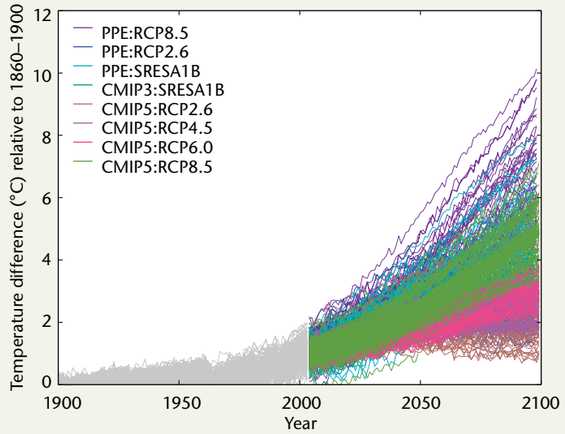

Figure 8: Time series of warming relative to 1860–1900 for the CMIP5, CMIP3 and Met Office Hadley Centre perturbed physics ensemble (PPE) models for a range of scenarios.
Historical simulations are shown in grey.

Heavier summer downpours with climate change

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Apex

Better information on potential future risks is being provided to inform decision making.

The IPCC AR5 concluded that it is likely that heavy rainfall is increasing over the majority of land areas globally. This is based on observations and modelling studies on daily timescales. However, how changes will manifest themselves on hourly timescales remains highly uncertain. This is of concern since short but intense periods of rainfall can lead to flash flooding with devastating impacts.

New work at the Met Office Hadley Centre is allowing us to examine changes in these intense rainfall events for the first time. A spatially very detailed model has been used to examine changes over the southern UK. This model, unlike typical climate models, is able to realistically represent hourly rainfall, allowing us to make future projections with more confidence (Figure 9).

Basic physics tells us that a warmer atmosphere is able to hold more moisture – at a rate of approximately 7 per cent increase per degree warming – as described by the Clausius–Clapeyron equation. This is expected to lead to similar percentage increases in heavy rainfall, which has generally been borne out by models and observed changes in daily rainfall. However, increasing evidence from observations suggests that the intensity of hourly rainfall extremes may increase more rapidly with temperature. This may be explained by latent heat released within storms invigorating vertical motion, leading to greater increases in rainfall intensity.

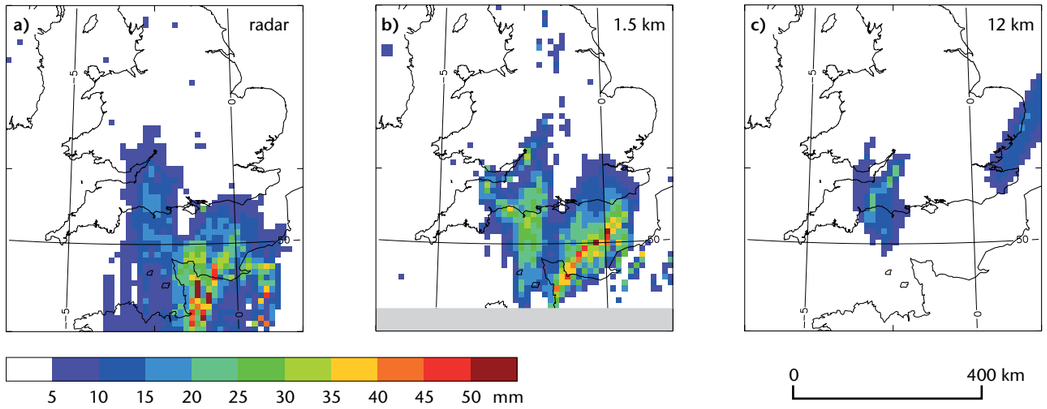

Figure 9: Heavy rainfall on 27 July 2013 from (a) radar observations, (b) 1.5 km forecast model, and (c) 12 km model. The improvement seen in the 1.5 km model forecast is typical for convective storms.

These highly detailed climate model experiments provide the first evidence that summer downpours could become heavier with climate change. While summers are expected to become drier overall by 2100 over the UK, results show that when it does rain it will be heavier (Figure 10). In particular, the model suggests intense rainfall associated with flash flooding (more than 30 mm in an hour) could become almost five times more frequent.

This work provides a first look at how convective storms, not just in the UK but potentially elsewhere, may change as the atmosphere warms.[2] The study is based on one model, so we need to wait for other research institutes to run similarly detailed simulations to see whether their results support these findings. However, the results are consistent with the theory of an intensification of summertime convective events in a warmer, moister environment and with the limited observational studies of hourly rainfall to date.

Improved projections are needed so we can make informed decisions on managing the risks associated with heavier rainfall due to climate change. The UK has experienced several major summer flood events in recent years, representing a considerable loss to the UK economy. A significant proportion of these has been associated with short-duration intense events, important in small catchments and urban areas. Annual damages from flooding are estimated to rise substantially in the absence of appropriate mitigation and adaptation measures. This work will lead to better estimates of potential future flood losses and therefore better targeted use of resources to reduce those losses and increase resilience.

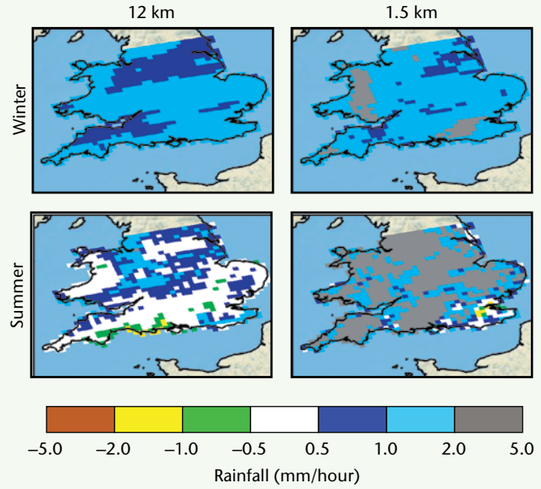

Figure 10: Future changes in heavy rainfall at the hourly timescale in the 12 km (left) and 1.5 km (right) models, for winter (top) and summer (bottom). Both models show increased hourly rainfall intensity during winter, but the 1.5 km model also reveals significant increases in short-duration rain intensity during summer. Changes are for the end of the century under high emissions scenario RCP8.5.

[2] This work has been carried out in collaboration with the Natural Environment Research Council (NERC) as part of the CONVEX (Convective Extremes) project.

Future climate impacts

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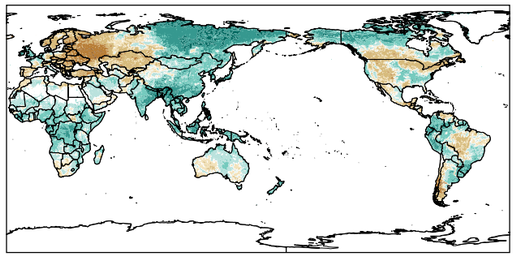
Future climate impacts will affect many aspects of daily life. For better planning, the full range of possible impacts needs to be considered.

Climate change is already having impacts on natural systems. For example, many species have shifted their geographic ranges and seasonal activities in response to a changing climate. There is also some evidence for climate change impacts on human systems but non-climate factors are currently more important. Climate change is projected to amplify existing climate-related risks and create new risks for natural and human systems, and better understanding the range of potential further changes is now a priority.

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) was used in the recent IPCC assessment and is the first internationally coordinated effort to look at impacts across a range of sectors from multiple models. Sectors examined include agriculture, water, ecosystems and health. ISI-MIP aims to improve on earlier work by characterising the uncertainties in climate modelling with the uncertainties in impacts models. Additionally, it enables impacts from different sectors and regions to be easily compared.

A first look by the Met Office Hadley Centre at changes in flooding using ISI-MIP shows that fluvial flooding is projected to increase over more than half of the globe with climate change (Figure 11). In up to 30 per cent of land regions, the current 1-in-30 year flood is projected to become at least as frequent as 1-in-5 years by the end of the century under a high emissions scenario (RCP8.5). Flooding does not increase everywhere. Decreases are found over roughly one-third of the global land regions, particularly in areas dominated by spring snowmelt. This work uses coarse resolution climate model projections, unlike in the previous study (p. 12), and so does not represent local convective storms. Although important for flash flooding, convective storms are less important for large-scale river (fluvial) flooding. The global results for ISI-MIP reflect changes in snowmelt, frontal systems and wet spells.



Number of models agreeing on increase (blues) or decrease (browns) of a 1-in-30 year flood event

Figure 11: The number of models showing an increase (blues) or decrease (browns) in a 1-in-30 year flood event for 2070–99 relative to 1971–2000 for RCP8.5.
Data from ISI-MIP6. Projections of climate change impacts from ISI-MIP, in the context of a globalised world, are shown in the poster 'Human dynamics of climate change'. (www.metoffice.gov.uk/human-dynamics).

Work within ISI-MIP has enabled an analysis of multi-sectoral climate impact hotspots[3], identifying where impacts from different sectors overlap, thereby increasing exposure and raising the pressure to adapt. For a mean global warming of 4 °C, some 11 per cent of the world population is subject to severe impacts in at least two different impact sectors. Uncertainty arising from the different impact models, however, is considerable.

Phase 2 of ISI-MIP is beginning and this will look at more sectors and more models. In this phase, the Met Office will contribute to work on crops, using our newly developed JULES crop model. This will enable the impacts of climate variability and change on crop productivity to be studied, as well as the impact of croplands on the climate itself.

[3] F. Piontek et al. 2013. Multisectoral climate impact hotspots in a warming world. *Proceedings of the National Academy of Sciences*, Vol. 111, 9, 3233–3238. doi:10.1073/pnas.1222471110.

Making better decisions on the basis of observed and future changes in climate.

The need for information and tools to enable society world-wide to cope with climate variability and change is real and urgent. Climate Service UK is the Met Office's response to the UN-led Global Framework for Climate Services call for National Met Services to take a central role in establishing national frameworks. It offers expert advice and bespoke climate information to help inform decisions and build capacity in developing countries. This is a foundation for international climate services, which are based on high-quality climate knowledge and information and developed through close engagement with those sensitive to climate variability and change. Here we highlight a few examples.

- PRECIS is the Met Office's regional climate modelling system designed to run on a PC. It can be easily applied to any area of the globe to generate detailed climate change information, and therefore help with climate change adaptation decisions. PRECIS, and associated training on climate variability and climate change, has been used by over 70 developing countries to build their in-country knowledge and tools, enabling them to conduct their own climate simulations.

- The Climate Science for Service Partnership: China (CSSP: China) is a scientific research programme — led in the UK by the Met Office — that will help build the basis for services to protect against climate variability and prepare for a changing climate. Through CSSP: China (supported by the UK's Department of Business Innovation and Skills (BIS) UK-China Research and Innovation Partnership Fund) we are developing a strongly bi-lateral partnership between the Met Office, the China Meteorological Administration, the Institute of Atmospheric Physics at the Chinese Academy of Sciences, and other key institutes within China and the UK. The partnership will focus on research and innovation, establishing a firm foundation of cutting-edge science that can underpin the development of climate services to support climate-resilient economic development and social welfare, and enable the UK to develop strong, sustainable and systemic relationships with partner institutions.

- The Met Office leads the European Commission-funded EUPORIAS project working with a number of European stakeholders to develop prototype climate services to address the needs of specific users. The project aims to increase the resilience of European society to climate variability and change by demonstrating how climate information can become directly useable by decision makers in different sectors.

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